Neural Network Based Transient Stability Model to Analyze The Security of Java-Bali 500 kV Power System

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Abstract— **A transient stability model based on back propagation neural network is used to analyse transient stability of Java-Bali electricity system, especially in calculating the critical clearing time. Inputs used for the neural network is the real and the active variable load power, whereas the target of the neural network is the critical clearing time (CCT). Data of target CCT used for the training was calculated using the concept of One Machine Infinite Bus (OMIB), which is the reduction of multi-machine system in combination with the method of equal area criterion (EAC) through the Trapezoid method and the 4th Order Runge-Kutta method. The position and type of disturbance is assumed not changed. This model was tested on 500 kv Java-Bali system with type of disturbance is 3 phase ground fault. The results indicate that the approximate value of the CCT calculated by the proposed method has a minimum error of 0% and maximum error of 0.0008% compared with CCT by OMIB.**

Keywords — **transient stability, multimachine, one machine infinitive bus, equal area criterion, neural network.**

I. Introduction

In recent years, research on the transient stability problem revolves around the identification of critical machine, CCT and system transient stability modelling. A transient stability study with random variables is performed in [14], with linear approach involving the calculation of sensitivity derived from the CCT system. The study uses a complex reduction equation to determine the possibility of the system experiencing transient conditions. Determination of conditions of transient stability using multilayer perceptron artificial neural network studied in [15]. However, some weakness occurred in the determination of transient conditions of the system grouped by high and low class such that it did not accurately give a prediction value of CCT

Recent issues on the transient stability are how to calculate the CCT quickly and accurately, so that it can be applied online. In previous studies, most calculation was done using the conventional methods with complex equation. This study is trying to implement neural network using method based on back propagation to calculate critical clearing time of the system transient stability. By using BP neural network, it is expected that calculations can be carried out online and in less amount of time.

II. Methodology

A. General Methodology

The general methodology can be seen in figure 1. It starts from reading the data. The necessary data are power system network, data of generators, and load data. All this data is required for power flow studies to determine the voltage and phase angle and the loading of each bus before the disturbance. So, the performance of initial system was knowable.

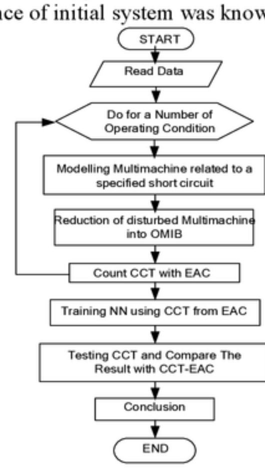

Fig. 1 Determination Flowchart of CCT

The next step is the modelling of transient stability. Modelling machines for transient stability condition is done by giving three phase short circuit on one bus. The Severely Disturbed Machine can be determined by observing the acceleration of the machine when the disturbance is happened.

It is necessary to reduce the modelling machine into one machine, because it can simplify to solve problems, and then classify the machines into two groups, the critical machine and non-critical machine. Two machines groups, then, is reduced into one machine infinite bus and the Critical Clearing Time can be calculated with a combination of OMIB equal area criterion via the trapezoidal method and the 4th Order Runge Kutta method.

Neural network (NN) is trained using CCT of OMIB-EAC obtained from the previous step. After training, the NN model will be tested using new operation condition to compute CCT. The results of testing CCT-NN will be compared with CCT-OMIB-EAC.

B. Detail Methodology

1) Modelling Multimachine for Transient Stability

Transient stability in power systems is the system's ability to maintain operating conditions when large disturbances occur. Disturbance in the system can cause major changes in the angle rotor and systems. Failure to manage the interference will result in loss of synchronization between machines. Machine stability limit is different from one another.

By looking at the stability limit of the worst machines, then the system transient stability can be determined. Machines that have the lowest stability limit is the most critical machine that has a tendency to initiate instability and loss of synchronization on the system. As a result, other machines will be affected and lose synchronization also form a group of machines that are not stable in the system. Mathematical modelling of machine dynamics [illegible]e-i with reference to the COA (Centre of Angle) is written as follows,

$$\frac{d\delta_i}{dt} = \omega_i \tag{2.1}$$

$$M_i \frac{d\omega_i}{dt} = P_i - P_{ei} - \frac{M_i}{M_T} \tag{2.2}$$

$$P_i = P_{mi} - E_i^2 G_{ii}$$

$$P_{ei} = \sum_{j=1}^{n} (C_{ij} \sin\delta_{ij} + D_{ij} \cos\delta_{ij})$$

$$M_T = \sum_{i=1}^{n} M_i$$

where,

C_{ij} = $E_iE_jB_{ij}$
D_{ij} = $E_iE_jG_{ij}$
E_i = internal voltage generator
δ_i = rotor angle
δ_{ij} = $\delta_i - \delta_j$
ω_i = velocity
P_{mi} = prime mover
M_i = inertia constant
B_{ij} = conductance (of the matrix impedance already reduced)
G_{ij} = susceptance (of the matrix impedance already reduced)

The right hand side of equation (2.2) is called P_{ai} acceleration power machine.

$$P_{ai} = P_i - P_{ei} - \frac{M_i}{M_T} P_{COA} \tag{2.3}$$

By eliminating the free variable t in equations 2.1 and 2.2, the differential equations between δ_i and ω_i can be written as follows,

$$M_i\omega_i \, d\omega_i = P_{ai} \, d\delta_i \tag{2.4}$$

2) Reducing into One Machine Infinite Bus (OMIB)

Conventional methods of analysing the stability have some weakness such as computing time is longer, lack of information about the sensitivity and control. To cover the weakness above, researchers developed several methods such as Lyapunov in the early 1960s. Then the method of EAC (Equal Area Criterion) which was upgraded in 1980, with multi-machine system is converted into One Machine Infinite Bus (OMIB).

In this research, a better method decomposing the multimachine system into two machine and then joint two machines into One Machine Infinite Bus (OMIB) will be used. This method will generally divide the plants into two groups, namely group of critical machines (generators are responsible for the loss of synchronization) and non-critical group of generators (power remaining) and finally joint both resulted groups into one machine to infinite bus. Several stages of this method is as follows,

1. Perform short circuit simulation to obtain the stability condition of machinery and machine grouping into two groups namely the critical machines and non-critical machines
2. Modelling group of critical machines into one machine model and non-critical machines into one machine model also
3. Two models of machines were reduced back to one model of machine to infinite bus.

The method to divide the multimachines into two groups is based on machine acceleration power looked at the post fault condition. Machine i can be categorized into one of the Severe Disturbed Machine Group if it satisfies the following equation

$$\frac{|a_i^f|}{a_{max}^f} > a \tag{2.6}$$

a_i^f is the acceleration of the i-th machine at the time of disturbance, a^f_{max} is the maximum acceleration value of machinery and α is the tolerance allowed (the value of 0.7 is sufficient to provide satisfactory results) [6]. Acceleration of the machine can be obtained by dividing power with the constant inertia machine acceleration.

Procedures for determining the critical machine is,

a. Calculate the acceleration of post-fault power of all SDM using equation 2.3.
b. Machine with SDM acceleration power through the zero line was considered as a critical machine.

Equations to form OMIB are given as follows. Centre of Angle (COA) for critical machine rotor angle δ is defined by the following equation,

$$\delta_C = \frac{1}{M_C} \sum_{k \in C} M_k \delta_k \quad (2.7)$$

Centre of Angle (COA) for the rotor angle δ of non-critical machine is defined by,

$$\delta_N = \frac{1}{M_N} \sum_{j \in N} M_N \delta_N \quad (2.8)$$

Rotor angle δ of OMIB is given by the equation,

$$\delta_{OMIB} = \delta_C - \delta_N \quad (2.9)$$

Electrical and mechanical power output of generator at OMIB system given by the following equation,

$$P_e = M(\frac{1}{M_C} \sum_{k \in C} P_{ek} - \frac{1}{M_N} \sum_{j \in N} P_{ej}) \quad (2.10)$$

$$P_m = M(\frac{1}{M_C} \sum_{k \in C} P_{mk} - \frac{1}{M_N} \sum_{j \in N} P_{mj}) \quad (2.11)$$

Power acceleration at OMIB system was defined by the following equation,

$$P_a = P_m - P_e \quad (2.12)$$

Moment inertia of the critical engine is defined by,

$$M_C = \sum_{k \in C} M_k \quad (2.13)$$

Moment inertia of non-critical machine is determined as follows,

$$M_N = \sum_{j \in N} M_j \quad (2.14)$$

Moment of inertia of OMIB system is as follows,

$$M_{OMIB} = \frac{M_C M_N}{M_C + M_N} \quad (2.15)$$

3) Computing Critical Clearing Time (CCT) using Equal Area Criterion (EAC) via The Trapezoidal Method and The 4th Order Runge-Kutta Method

Trapezoidal method is used to determine the critical angle of the equivalent OMIB generator. In this method, the curve is approached by a number of straight lines, form in many layers as in Figure 2.

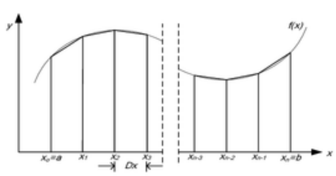

Fig. 2 Trapezoidal method with many layers

Total area is the sum of the layers area. The smaller divisions of the trapezoid area, more accurate results are obtained. If there are n layers, mean of layers is:

$$\Delta x = \frac{b-a}{n} \quad (2.16)$$

Δx is length of each layer.

A three phase short circuit fault occurs at the sending end, caused no power is deliver to the infinite bus. Electrical power Pe is zero, and the power angle curves same with the horizontal axis. Machine is accelerated by total input power and same with power acceleration thus increasing the speed, storing kinetic energy and raises the angle δ_o.

When the disturbance is removed at the point of δ_c, which shifts the operating point to the initial power angle curve at point e. Net power is now declining, and its kinetic energy will reach a zero value at the point f, when the shaded area (defg), characterized by A_2, same with the shaded area (abcd), characterized by A_1. Since P_e is greater than P_m, the rotor will continue to slow in line-power angle curve past the point of e and a. Because the effects of damping, the oscillations slowed and the operating point back to the point of initial power angle δ_0.

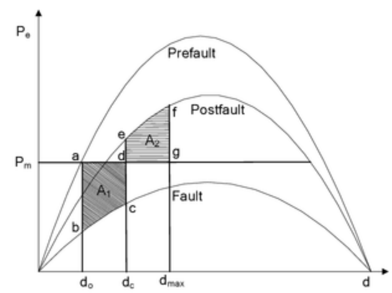

Fig. 3 Equal Area Criterion for 3 phase fault short circuit the end of the sending end.

Termination of the critical angle is achieved if the increase δ_l cause the area A_1, which shows the deceleration area, smaller than the area that shows the acceleration energy. This occurs when δ_{max}, or point of f, is at an intersection between the lines P_m and curves P_e, as shown in Figure 3. By using the equal area criteria, it was found,

$$\int_{\delta_o}^{\delta_c} P_m d\delta = \int_{\delta_c}^{\delta_{\max}} (P_{\max} \sin\delta - P_m) d\delta \quad (2.17)$$

be integrated equation , then obtained ,

$$P_m(\delta_c - \delta_o) = P_{\max}(\cos\delta_c - \cos\delta_{\max}) - P_m(\delta_{\max} - \delta_c)$$

so the equation will be obtained for

$$\cos\delta_c = \frac{P_m}{P_{\max}}(\delta_{\max} - \delta_o) + \cos\delta_{\max} \quad (2.18)$$

The 4th Order Runge Kutta is used to determine the critical clearing time (t^{cr}) of OMIB based on δ_c which has been established in previous processes. To determine the value of x_i using 4th Order Runge Kutta first, determine the following four constants,

$$k_1 = f(t_i, x_i)\Delta t \quad (2.19)$$

$$k_2 = f(t_i+(0.5)\Delta t, x_i+(0.5)k_1)\Delta t \quad (2.20)$$

$$k_3 = f(t_i+(0.5)\Delta t, x_i+(0.5)k_2)\Delta t \quad (2.21)$$

$$k_4 = f(t_i+\Delta t, x_i+k_3)\Delta t \quad (2.22)$$

then, $x_{i+1} = x_i + (1/6)*(k_1+2k_2+2k_3+k_4)$

Critical Clearing Time (t^{cr}) as follow:

$$k_1 = f(\delta_i,\omega_i)\Delta t = \omega_i \Delta t$$
$$l_1 = g(\delta_i,\omega_i)\Delta t = (\pi f/H_i)*P_a^f(\delta_i)*\Delta t$$
$$k_2 = f(\delta_i+0.5k_1,\omega_i+0.5l_1)\Delta t = (\omega_i+0.5l_1)*\Delta t$$
$$l_2 = g(\delta_i+0.5k_1,\omega_i+0.5l_1)\Delta t = (\pi f/H_i)*P_a^f(\delta_i+0.5k_1)*\Delta t$$
$$k_3 = f(\delta_i+0.5k_2,\omega_i+0.5l_2)\Delta t = (\omega_i+0.5l_2)*\Delta t$$
$$l_3 = g(\delta_i+0.5k_2,\omega_i+0.5l_2)\Delta t = (\pi f/H_i)*P_a^f(\delta_i+0.5k_2)*\Delta t$$
$$k_4 = f(\delta_i+k_3,\omega_i+l_3)\Delta t = (\omega_i+l_3)*\Delta t$$
$$l_4 = g(\delta_i+k_3,\omega_i+l_3)\Delta t = (\pi f/H_i)*P_a^f(\delta_i+k_3)*\Delta t$$

then, the value of and ω is,

$$\delta_{i+1} = \delta_i + (1/6)*(k_1+2k_2+2k_3+k_4)$$
$$\omega_{i+1} = \omega_i + (1/6)*(l_1+2l_2+2l_3+l_4)$$

where, $\delta_1 = \delta^0$ and $\omega_1 = 0$

By increasing t from 0 to 1 second using a small Δt it will be found CCT (t^{cr}). Iteration will stop if $\delta_n = \delta^{max}$

4) *Training Neural Network*

Backpropagation Learning Neural Network performed using Matlab software. Network architecture of the neural network consists of several inputs that are the incremental of active and reactive load that can be added to the system as long as does not exceed the capacity of the system.

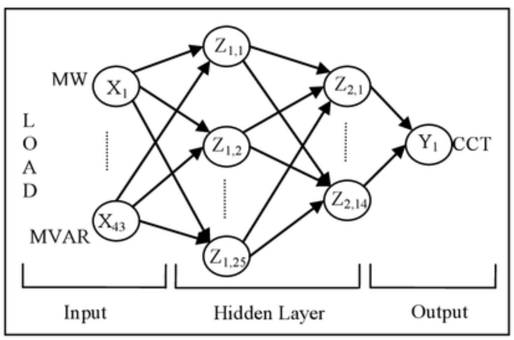

Fig. 4 Backpropagation Neural Network Architecture Network

The output of the neural network is CCT as the target. From the overall 49 existing data, only 43 data will be used to train the NN, while the rest 6 data will be used as testing data.

Momentum backpropagation will be used for neural network training process which is composed of 30 inputs, two hidden layers and one output layer. Inputs consist of 30 neurons, each of which represents active or reactive load system. The hidden layers consist of two layers. The first layer of hidden layer consists of 25 neurons with activation function tansig. The second layer consists of 14 neurons with activation function logsig. Output layer consists of a single neuron with activation function purelin.

III. Implementation

The system used in this study is the Java-Bali interconnection 500kV. This system consists of 23 buses with 28 mesh transmission and 8 generators as can be seen in figure 5.

Fig. 5 Diagram of the Java-Bali interconnection system lines 500 kV

The generators are Suralaya, Muaratawar, Cirata, Saguling, Tanjungjati, Gresik, Paiton, and Grati. Among these eight plants, power plants Saguling Cirata are water power plants, while others are steam power plants. In this study Suralaya power plant act as a slack generator.

The load data obtained from PT PLN (Persero) [17]. The kV base is 500 kV, MVA base is 1000 MVA, and the system frequency is 50 Hz. Generator data used are shown in Tables 1.

Table 1

Generator Data

Generator Number	Generator Name	Xd' (pu)	H
1	Suralaya	0.297	5.19
2	Muaratawar	0.297	1.82
3	Cirata	0.274	2.86
4	Saguling	0.302	1.64
5	Tanjung Jati	0.2588	3.2
6	Gresik	0.297	2.54
7	Paiton	0.297	4.42
8	Grati	0.297	3.5

Step of implementation are as follows,

1. Java-Bali initialization data consisting of 500 kV active and reactive generator power, load power, reactance and admittance of transmission, the angle and voltage of the system.
2. Run Load Flow Program. Calculate the admittance matrix reduction prefault (before disturbance), the prime mover, voltage generator, and the initial angle generator.
3. Test the system using 3 phase ground fault disturbance on the bus load.
4. Calculate the admittance matrix reduction during interruption.
5. Open CB in network transmission to eliminate interference.
6. Calculate the admittance matrix reduction after disturbance.

7. Calculate the *i*-th machine acceleration during disturbances, and the maximum value of acceleration machine. If the ratio between the value of the *i*-th machine acceleration and maximum acceleration is larger than α (eq.2.6), those values machines are categorized critical; if not then there is no critical machine and end the program.
8. Check the maximum electrical power and mechanical power of critical machine. If the maximum electrical power is greater than the mechanical power than the critical machine is stable and end the program, otherwise then analyzed using OMIB.
9. Calculate the Critical Clearing Angle (CCA) using the Equal Area Criterion (EAC) via the trapezoidal method.
10. Calculate the critical clearing time (CCT) of OMIB using Runge-Kutta 4th order.
11. Repeat the above steps for other load operation condition
12. Training Neural Networks using load change data as input and CCT as output
13. Test the proposed method and compare the result
14. Comparing CCT OMIB-EAC with the CCT-NN

IV. RESULT ANALYSIS

Simulation was done by conducting short circuit at bus Gandul and the line between bus Gandul and bus Cibinong was terminated momentarily. Gandul-Cibinong was selected due to its susceptibility to short circuit fault. Alternating the load was done at bus Pedan by increasing it gradually from 0.25% until maximum of system load was achieved. The simulation results indicated that an increase of up to maximum 12% was reached without violating the nominal load limit of the system. Some of the results can be referred to table 2.

TABLE 2

CRITICAL RESULTS OF CCT TO THE INCREASE IN LOAD

NO	LOAD		CCT (s)	NO	LOAD		CCT (s)
	MW	MVAR			MW	MVAR	
1	524.00	244.00	0.1540	7	537.24	250.16	0.1490
2	525.31	244.61	0.1540	8	539.93	251.42	0.1490
3	526.62	245.22	0.1530	9	542.64	252.68	0.1480
4	529.25	246.44	0.1520	10	543.99	253.31	0.1470
5	534.57	248.92	0.1510	11	546.72	254.58	0.1470
6	535.90	249.54	0.1500	12	552.20	257.13	0.1450

Next step is training step of BP neural network. Improved Neural Network output value which reflects the results of the learning process can be seen from the changes in the value of MSE (Mean of Squared Error) in each accretion epoch. Neural Networks are trained to achieve the minimum MSE or maximum epoch is reached.

Next, the value of critical clearing time in the system obtained from the calculation method OMIB-EAC, compared with results obtained by training using the method of BP Neural Network. The 43 data used for the training process. Some of the comparison CCT can be seen in Table 3.

TABLE 3

COMPARISON TRAINING CCT USING OMIB-EAC METHOD AND NEURAL NETWORK

NO	LOAD		TRAINING CCT (s)	CCT OMIB-EAC (s)	ERROR (%)
	MW	MVAR			
1	524.00	244.00	0.1541	0.1540	0.0008
2	525.31	244.61	0.1536	0.1540	0.0023
3	526.62	245.22	0.1532	0.1530	0.0014
4	529.25	246.44	0.1524	0.1520	0.0029
5	534.57	248.92	0.1507	0.1510	0.0023
6	535.90	249.54	0.1500	0.1500	0.0000
7	537.24	250.16	0.1494	0.1490	0.0027
8	539.93	251.42	0.1486	0.1490	0.0027
9	542.64	252.68	0.1478	0.1480	0.0016
10	543.99	253.31	0.1474	0.1470	0.0027
11	546.72	254.58	0.1467	0.1470	0.0023
12	552.20	257.13	0.1446	0.1450	0.0030

From the table 3 it can be seen that the minimum error was 0%, and maximum error is 0.003%. The average error of neural network training to OMIB-EAC method is 0.001816279. Graphically, the comparison accuracy of the output value of the CCT using the method OMIB-EAC and Neural Network can be seen in Figure 6.

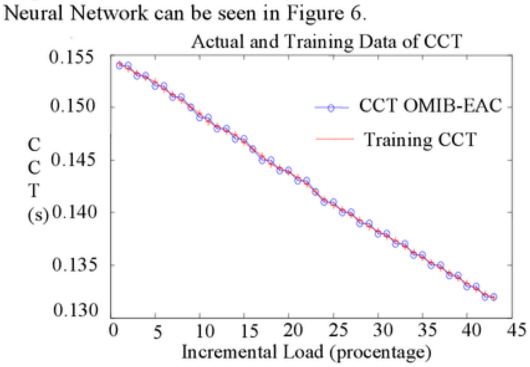

Fig. 6 Graph comparison of CCT results OMIB method and BP Neural Network (NN) method

In Figure 6 it appears that the estimation value of CCT resulted using BP neural network is very similar with the CCT values calculated using the method OMIB-EAC with a very small difference.

Next, testing is conducted to compute the CCT using data which are not trained. The result of this testing step can be seen in table 4.

TABLE 4

COMPARISON CCT TESTING AND CCT OMIB-EAC

NO	LOAD		TESTING CCT-NN (s)	CCT OMIB-EAC (s)	ERROR (%)
	MW	MVAR			
1	530.58	247.06	0.1521	0.1520	0.0005
2	538.59	250.79	0.1490	0.1490	0.0002
3	545.35	253.94	0.1471	0.1470	0.0006
4	550.83	256.49	0.1449	0.1450	0.0008
5	564.75	262.97	0.1400	0.1400	0.0002
6	571.85	266.28	0.1380	0.1380	0.0000

From the CCT-NN testing simulation, the minimum error obtained is 0.0000 and a maximum error is 0.0008. The average of error testing is 0.00028333. Simulation results can be seen in the figure 7 below.

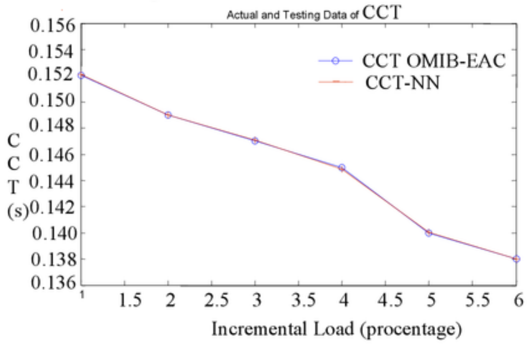

Fig. 7 Comparison of CCT-NN and CCT OMIB-EAC

Comparing the value of CCT-OMIB-EAC with CCT- NN at figure 7, it can be concluded that both values are mostly located in the same position. The best results are shown with error 0.0000

V. CONCLUSION

1. Neural Network model used to estimate the value of cct provide accurate results with maximum error 0.0008% and a minimum of 0% error
2. The accuracy of transient stability analysis on the Java-Bali interconnection system using the proposed method is good only for the same location of 3 phase ground fault. It is recommended to develop the research in the future by accommodating variable short circuit location.

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